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LANDSLIDING IN MARINE TERRACE TERRAIN, CALIFORNIA

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Special Report 119

LANDSLIDING IN MARINE TERRACE TERRAIN, CALIFORNIA

By

George B. Cleveland

1975

California Division of Mines and Geology
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ABSTRACT

Marine terraces form a belt along much of California's coast. Nearly all coastal communities are built, at least in part, on terraces making this belt one of the most valuable land areas in the State.

Erosive energy concentrated locally along stream courses and along former shorelines has yielded ancient and modern bedrock landslides in the terrace terrain. The geomorphic model, offered here to explain the origin of landslides along stream courses, is based on the premise that these landslides are largely related to stream development. Younger landslides occur along streams with relatively low flow rates that have been late in establishing a channel to the sea after emergence of the terrace. Ancient landslides occur generally along streams with relatively high flow rates. These streams have maintained a nearly continuous channel to the sea during several periods of sea level fluctuation. Landsliding may be accelerated along stream courses where the width of the terrace belt has been reduced by marine erosion and where stream gradients have been steepened. Locally, cementation of terrace deposits and buttressing by stream deposits, talus, and fanglomerates have led to relatively stable slopes.

In addition to analyzing other landslide mechanisms, slope stability evaluation in terrace terrain can be refined by analyzing terrace evolution and drainage development with respect to relative sea level fluctuations.

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LANDSLIDING IN MARINE TERRACE TERRAIN, CALIFORNIA

by George B. Cleveland

INTRODUCTION

Regional planning in California requires an understanding of the occurrence and nature of landslides. Because most landslide debris is unstable, knowledge of the distribution of landslides is important if they are to be avoided, or if they are to be utilized under controlled engineering conditions. Moreover, some measurement of the relative stability of slopes is necessary as a means of predicting where future landslides are most likely to occur.

Most of the coast of California is marked by marine terraces which were cut by the sea during times when sea level was relatively higher with respect to the land than it is today (figure 1). These terraces, which are generally flat and lie adjacent to the shoreline, comprise some of the most valuable land resources in the State. Most of California's coastal communities are built, at least in part, on such terraces.

The terraces form a belt of newly emerged terrain along the coastline across which streams must flow from highland areas to reach the sea. These surfaces interrupt stream flow in a way that concentrates the erosive energy in certain places, leading to the development of bedrock landslides. A review of landslide distribution shows that landslides develop locally along these stream courses (figure 2). The origin of landslides appears to be related to sequences of events that take place during the development of the drainage of different groups of streams on the terraces. In addition, landsliding is largely restricted, both in space and time, with respect to certain stages of drainage development. The recognition of the stream group, the associated sequence of events, and the determination of the stage of drainage development, among other factors, appears to be useful in appraising natural slope stability on and adjacent to marine terraces.

This paper is based on reconnaissance field inspection and air photo interpretation of areas along the San Diego, Los Angeles, Ventura, Santa Barbara, San Luis Obispo, Santa Cruz, San Mateo, Sonoma, and Mendocino County coasts. It also includes observations made during studies in the Palos Verdes Hills area of Los Angeles County (Jahns and Cleveland, 1962; Cleveland, 1967) and the San Clemente area of Orange and San Diego Counties (Blanc and Cleveland, 1968).

ACKNOWLEDGMENTS

I am indebted to Richard H. Jahns for introducing me to the geology of marine terraces and for reviewing this paper. I thank Rudolph G. Strand for his thoughtful review and for the many helpful discussions we have had related to landslide phenomena.

COASTAL TERRACES

Marine terraces are found along most of the California coast. The terraces are represented by broad continuous surfaces up to a few miles in width and several miles in length or are preserved locally as subtle benches on seaward facing mountain spurs. Commonly the terraces occur in a series of steps that range in elevation from a few feet to about 2000 feet above sea level. The well preserved terraces on the Palos Verdes Hills, in Los Angeles County (figure 3), comprise 13 main terraces and numerous minor, intermediate ones. The highest terrace lies at a present altitude above 1400 feet (Jahns and Cleveland, 1962). The terraces along the coast range from a few thousand to a few hundreds of thousands of years in age (table 1). A considerable period of time may lapse between the actual cutting of the terrace and the subsequent deposition of terrace deposits. Generally, it is the deposits that are dated.

The marine terrace terrain is defined here as a series of emerged wave cut platforms that parallel the coast and are generally covered with surficial deposits. Terrace is used in a general sense to indicate an individual platform in the terrace terrain. The back of the terrace is its landward limit, and the edge, its present seaward limit. The landward limit

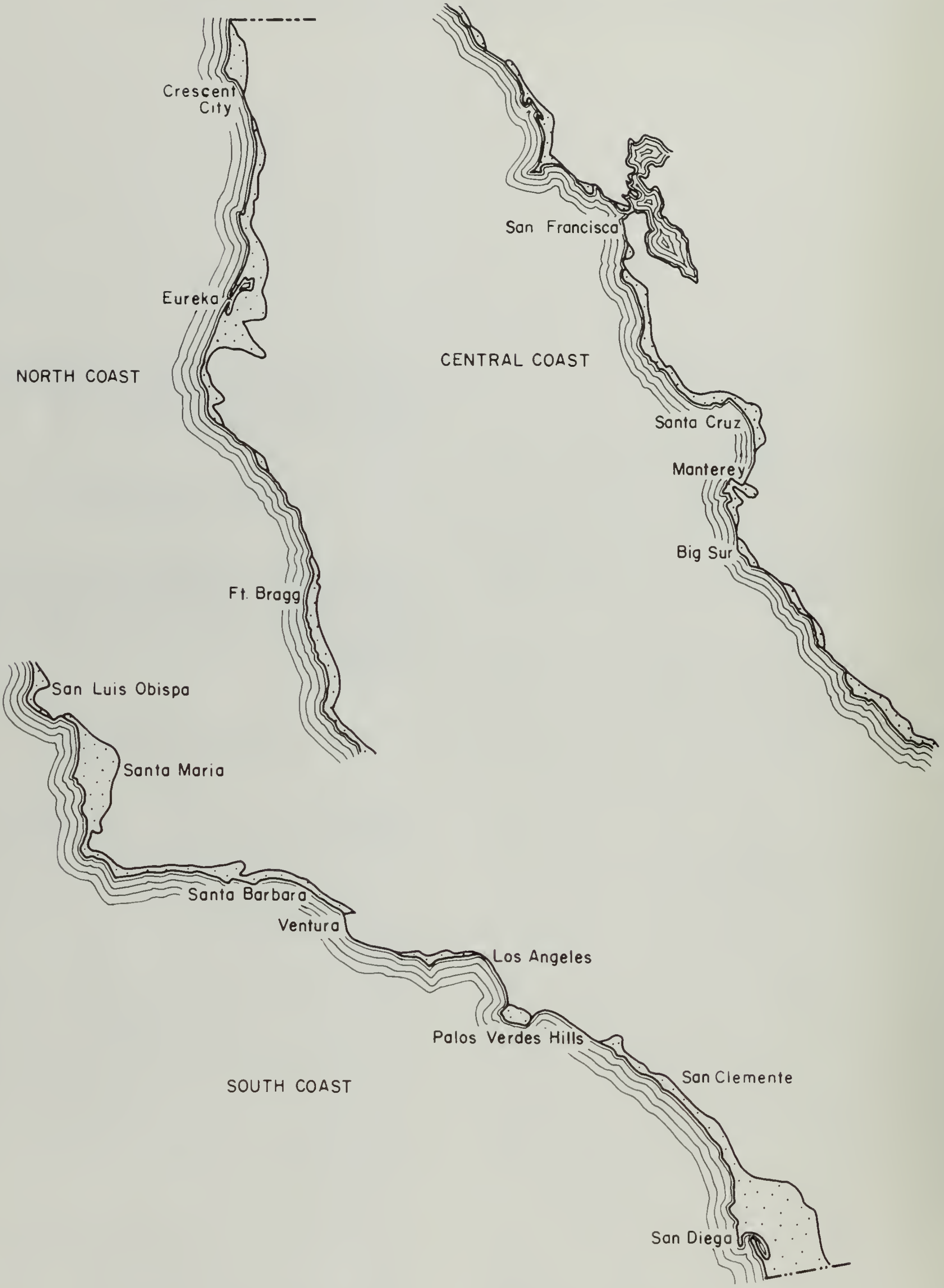


Figure 1. Marine terrace terrain, California. Generalized and modified from Palmer, 1967.

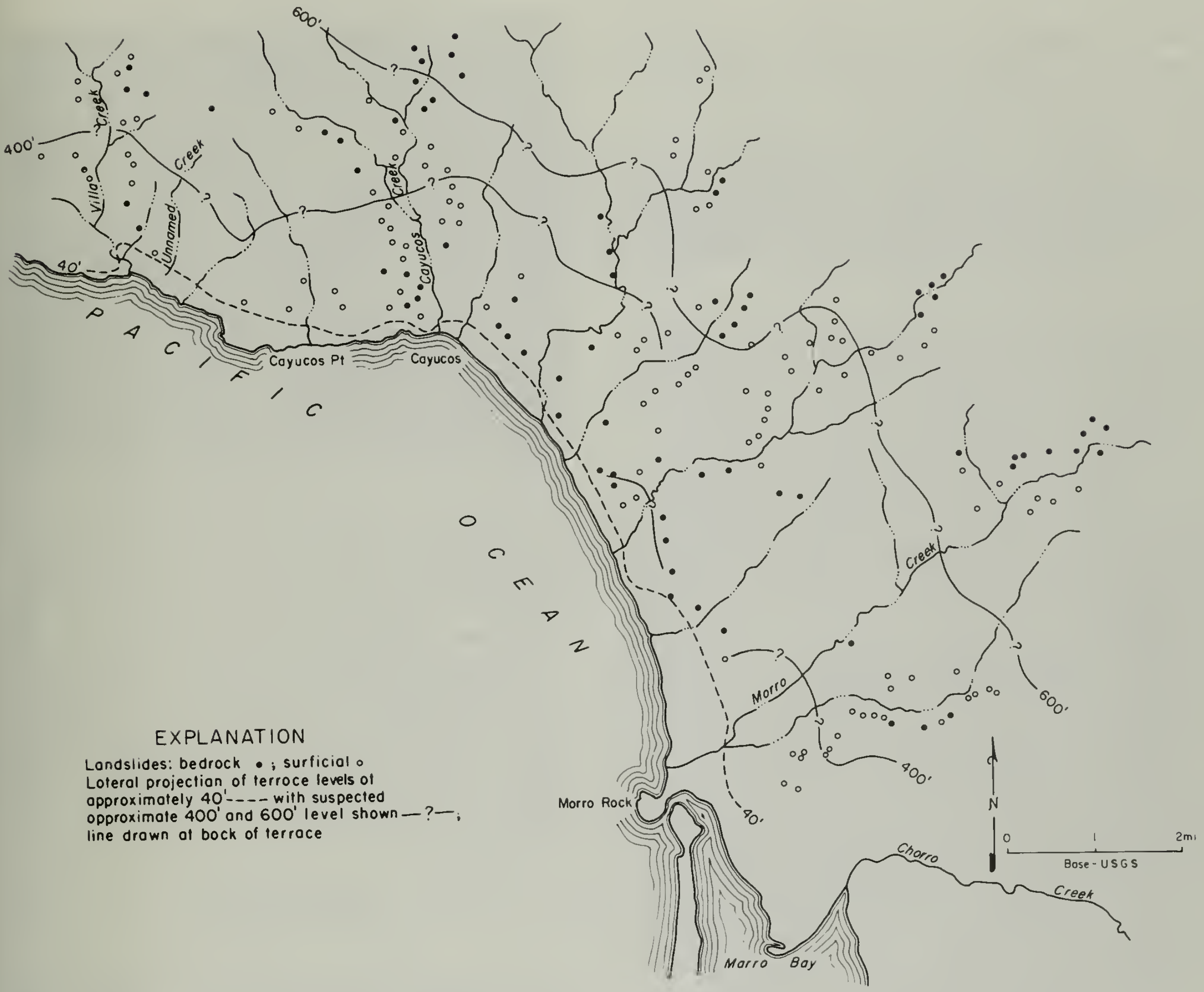

600'
400'
40'
Villa Creek
Unnamed Creek
Cayucos Creek
PACIFIC
OCEAN
Cayucos Pt
Cayucos
Morro Creek
Creek
600'
400'
40'
Morro Rock
Chorro Creek
Morro Bay
N
0
1
2mi
Base - USGS
EXPLANATION
Landslides: bedrock • ; surficial ○
Lateral projection of terrace levels at approximately 40' ---- with suspected approximate 400' and 600' level shown —?—; line drawn at back of terrace

Figure 2. Reconnaissance map. Landslides in terrace terrain along San Luis Obispo County coast.

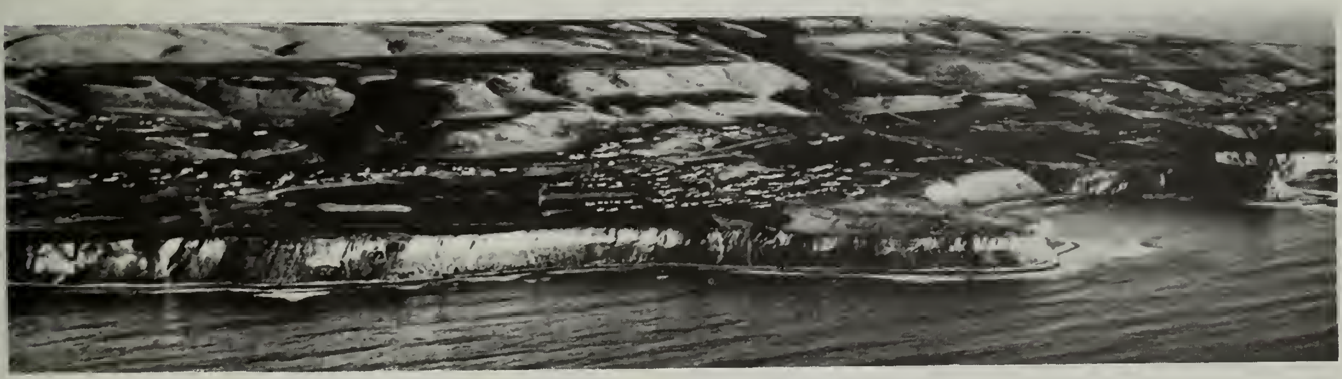


Figure 3. Marine terrace terrain, Palos Verdes Hills, Los Angeles County. *Photo courtesy of R.C. Frampton.*

Table 1. Geologic ages of selected marine terrace deposits in California.

Terrace (and present altitude)	Location	Geologic age* (thousands of years before present)	Reference
Palos Verdes Sand (100± feet)	Palos Verdes Hills, Los Angeles County	115±20	Valentine and Veeh, 1969
"12th Terrace" (1230 feet)	Palos Verdes Hills, Los Angeles County	380±50	Valentine and Veeh, 1969
"First Terrace" (100± feet)	Near Santa Cruz, Santa Cruz County	68±10 to 100±7	Bradley and Addicott, 1968
"Cayucos Terrace" (40± feet)	Near Cayucos, San Luis Obispo County	130 to 140±30	Veeh and Valentine, 1967
"Low Terrace" (80-85 feet)	San Nicolas Island, Ventura County	120±20	Valentine and Veeh, 1969

*All radiometric ages were determined from fossils in terrace deposits overlying the erosion platform, except at Santa Cruz where fossils in terrace deposits and those found just below the surface of the bedrock platform (boring organisms) were dated.

is generally marked by an abrupt change in slope, which ordinarily is an ancient sea cliff. No distinction is made here between the term terrain and the alternate spelling terrane. Formally, terrane was reserved for rock materials, but it is now considered obsolete (Gary and others, 1972, p. 731).

It is not always possible to determine whether eustatic drop in sea level or tectonic uplift has been primarily responsible for the present positions of the terraces. Therefore, the terraces are referred to here as emerged terraces and no special connotation is implied as to whether they are perched or uplifted features.

The terrace platform is generally veneered by relatively thin, poorly consolidated and sorted marine deposits. These deposits can be of all manner of rock debris, but commonly they are made up of rounded pebble to sand size fragments and, locally, of heavy walled marine fossils (figure 4). Bradley (1957) showed that the main marine terrace at Santa Cruz was cut during a rise in sea level, and that the marine terrace deposits were formed during a fall in sea level. This observation may prove to be valid for some or all marine terraces in California. Normally overlying the marine deposits is a nonmarine cover of alluvial debris derived from streams that empty out onto the terrace deposits. Generally, the surface of the nonmarine cover is relatively even over the terrace, preserving, with only minor undulations, the planar aspects of the buried platforms below. Only at the back of the terrace, adjacent to the ancient sea cliff which marks the former shoreline, have thicker deposits accumulated. They may form discrete alluvial fans, or, if the streams are closely spaced along the ancient sea cliffs and are transporting sufficient detritus from inland areas, the fans may coalesce to form alluvial aprons.

Most of the coast is hilly or mountainous where terraces are well developed. The mountain fronts facing the sea are some of the first areas to receive moisture-laden air from storms originating over the Pacific Ocean. Because elevation increases progressively inland, orographic cooling yields significant rainfall to the coastal slope. This rainfall leads to relatively large amounts of runoff in the stream courses that cut through the terrace terrain from inland areas and lesser amounts of runoff on the terrace surface itself. Moreover, being relatively flat, the terraces are drained by numerous minor stream channels. Flow in these streams is sluggish thus allowing a greater time for percolation than in areas of higher relief where the runoff along a few major drainage courses is rapid. Therefore, much of the precipitation that falls directly on the terrace percolates into poorly consolidated terrace cover. Commonly this ground water is held in sandy zones of these deposits or migrates down to the contact between the terrace deposits and the underlying bedrock platform. If the bedrock is less permeable than the overlying terrace deposits, ground water may accumulate at the interface. If the bedrock platform slopes gently seaward, which is generally the case, the ground water migrates locally in that direction. Seepage may occur at the sea cliffs or, if the ground water moves laterally, it will emerge along the banks of the major drainage courses that cut across the terrace surface. In both cases, the moisture can reduce the strength of the bedrock.

Characteristically, even in the driest areas, the gentle slopes and thick surficial rock and soil cover on terraces retain sufficient moisture to support grass. Locally in humid climate zones, larger plants grow on the terraces, especially along the north coast, where trees may be the predominant plant cover.

DRAINAGE

Certain streams that head well inland above the terrace terrain have established well-defined channels that cross the terraces to the sea. These streams are termed integrated streams. Those streams that have failed to establish such a connection with the sea are termed non-integrated streams. The integrated streams fall into two groups: Group I - those with relatively high flow rates that established a connection with the sea near the height of the glacial stages when sea level was low; and Group II - those that subsequently established a connection with the sea. It is along the channels of these two groups of streams that landslides most commonly occur. The non-integrated streams, Group III, are those that have not yet established a direct conduit to the sea. They may head above or within the terrace terrain but terminate by dissipating their flow into the terrace cover. The three groups of streams are characterized mainly by differences in the morphologic features of their channels (table 2).

Group I streams, which were graded to former low sea levels, cut deep channels and steep slopes as a result of abundant precipitation and runoff that characterized the climate during the glacial stages. Landslides were probably common along these

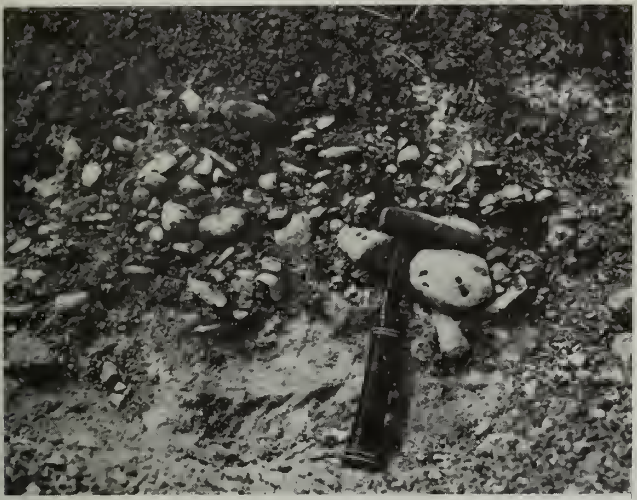


Figure 4. Typical cover on terrace platform composed of marine cobbles and pebbles in a sandy matrix, overlain by fine grained nonmarine alluvial deposits. Palos Verdes Hills, Los Angeles County.

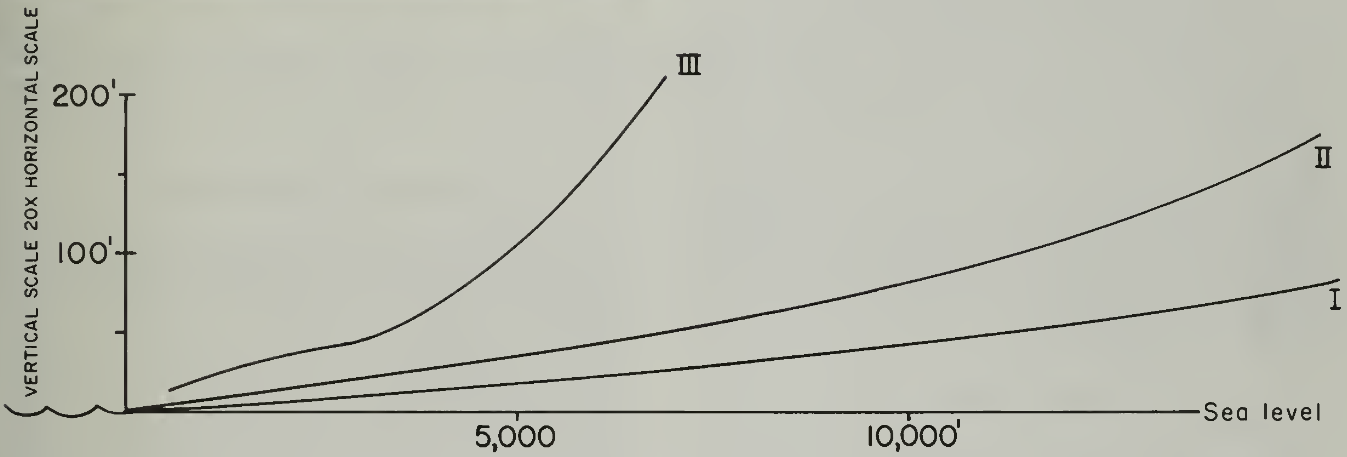


Figure 5. Typical stream profile of each stream group in terrace terrain.

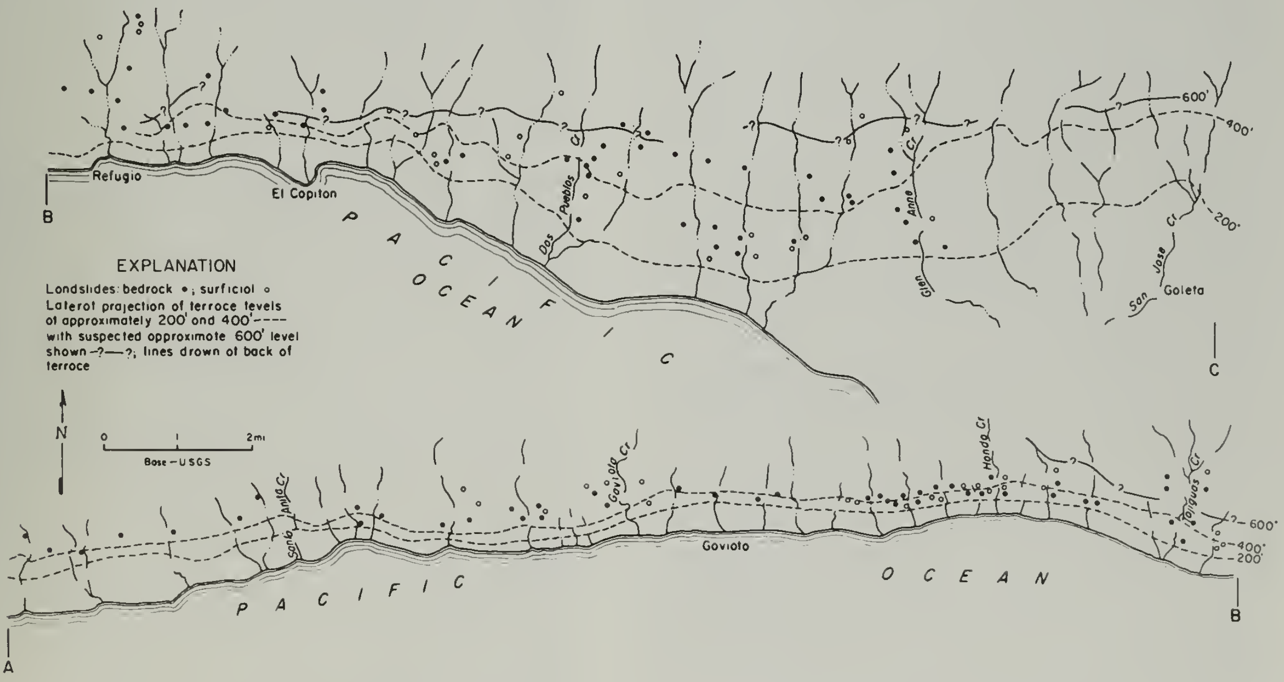

Refugio
El Capitan
B
Dos Pueblos Cr
Glen Anne Cr
San Jose Cr
Goleta
600'
400'
200'
C
PACIFIC OCEAN
EXPLANATION
Landslides: bedrock ●; surficial ○
Lateral projection of terrace levels of approximately 200' and 400' ---- with suspected approximate 600' level shown -?—?; lines drawn at back of terrace
N
0 1 2mi
Base—USGS
Santa Anita Cr
Gaviota Cr
Honda Cr
Tajiguas Cr
Gaviota
PACIFIC OCEAN
A
B

Figure 6. Reconnaissance map. Landslides in terrace terrain along Santa Barbara coast.

Table 2. Channel characteristics of streams in terrace terrain.

CHANNEL	STREAM		
	Group I	Group II	Group III[1]
Size	Relatively large; stream underfit.	Relatively small; stream flow generally ephemeral.	Minor; stream flow incipient and ephemeral.
Profile[2]	Gentle, smooth, and relatively uniform.	Steep to gentle and locally irregular.	Steep and commonly irregular.
Shape	Roughly parallel banks; width from terrace to terrace and from terrace to terrain inland somewhat uniform.	Interlocking spurs; increased width upstream at each junction with a higher terrace.	-----
Depth	Relatively deep.	Relatively shallow.	Very shallow.
Length	Extensive; generally miles to tens of miles long.	Relatively short; generally a few miles long.	Local; mainly limited to a single terrace or sea cliff.
Bottom	Flat and broad.	Rounded to "V" shaped; narrow.	"V" shaped.
Mouth	Commonly drowned.	Stream flows directly into sea.	Not connected with sea; stream flow dissipated mainly on alluvial fans.
Deposits	Thick alluvium at mouth and generally extending inland beyond terrace terrain. Large and generally old landslides; especially common directly inland from terrace terrain or just upstream of edge of next highest terrace.	Generally not alluviated. Relatively small and youthful bedrock landslides. Surficial landslides common.	Thick alluvial fan deposits at head of terrace.

[1] Stream flow on terraces largely in shallow channels on alluvial fans or as sheet flow.
[2] See figure 5.

major drainages when the volume of the channels enlarged to accommodate the high runoff. During the warming periods that followed glaciation, the major streams became underfit and, along with the influence of rising base level, aggraded their channels in the terrace terrain.

LANDSLIDES

Landslides in terrace terrain appear to be concentrated in certain places sometimes irrespective of lithology or structure. They occur along stream courses where the streams have cut deeply into the terrace terrain and are widespread along the modern sea cliffs; they are less common along the ancient sea cliffs. Bedrock landslides tend to cluster along the stream courses at the backs of the terraces; directly upstream from the terrace terrain; or, if there is a series of terraces, directly upstream from the edge of the next higher terrace (figure 2 and 6). Locally, along some deeply alluviated stream channels of Group I, landslides occur near the upstream boundary of the alluvial deposits where the stream profile steepens.

Landslides are progressively larger upstream with each terrace encountered because of the higher and older slopes, which affect a larger rock mass, and wider canyon floors which can accommodate a greater volume of slide debris. Although smaller slides occur where the slopes are lowest and the canyon bottoms narrowest, stream erosion locally may remove slide debris providing space for more debris and renewed landslide activity. Continuous or periodic removal of support in this manner may, in time, yield a landslide scarp of greater size than upstream where the channel is wider and where the debris has been preserved relatively intact, acting as a buttress to further movement.

Origin of Landslides

Landslides in the marine terrace terrain owe their origin basically to inherently weak parent rocks, but also to geologic and climatic events of the recent past and to the effects of modern geologic processes. The influence of ancient events on landsliding probably dates back several tens of thousands of years or more. These events yielded landslides, which are still preserved in the landscape, and established conditions that have perpetuated the landslide process to the present time. Where man indiscriminately has introduced his influence onto the terrace terrain, there commonly has been an accelerated deterioration of slope stability.

GENERAL CONSIDERATIONS

The origin of the landslides is intimately interwoven with the evolution of the terrace terrain. The terraces are a product, in part, of eustatic changes in sea level and, in part, of tectonic uplift or subsidence. Eustatic changes in the last several million years have followed numerous cycles that correspond to major climatic changes that date back to Pliocene time and probably earlier. Only the events that have occurred during the latest part of this time period have left a clear record and are amenable to analysis with respect to their influence on landsliding. Tectonic adjustment of the coastal margin has had an equally active history, but apparently not one that is as uniformly widespread along the coast as that of eustatic change. Nor has tectonic activity been necessarily synchronous with that of eustatic change. Aside from exhuming the seafloor locally and forming a terrace, tectonic uplift, as with eustatic lowering of sea level, would increase the erosive energy of streams by a relative lowering of base level.

Eustacy during the Pleistocene yielded numerous terraces and altered the regimen of coastal streams through changes in base level. For example, many investigators have recognized the "hundred foot" terrace, along the California coast at about this elevation, and terraces significantly higher and lower that range in age, but are, in general, approximately 100,000 years old (table 1 herein; Birkeland, 1972, p. 444). Thus, the age of the terraces roughly corresponds with the age of the Sangamon interglacial stage. With the onset of a colder and more moist climate during the Wisconsin glacial stage, sea level fell to a point 400 feet or more below present levels as continental ice accumulated. Streams reaching the sea at this time were graded to this lower level. Subsequently, as a warming trend developed, approximately 18,000 years ago, sea level began to rise. It reached to within a few tens of feet of present sea level 7000 years ago (Bloom, 1972). With rising sea level, the streams graded to lower levels began to aggrade their channels. Now most major streams along the coast are filled with alluvial debris tens to hundreds of feet deep near their mouths (Upson, 1949, 1951; Stout, 1969).

The rise in sea level following the Wisconsin has generally led to increased marine erosion along the California coast. In those areas where the rocks are inherently weak the sea has cut sea cliffs and intruded deeply into the coastal zone reducing the size of, or destroying, previously formed terraces. Locally this has altered stream regimens by advancing the mouth of the stream inland, and steepening its profile in the terrace terrain.

The rate of drainage development in the terrace terrain varies from place to place along the coast. The rate is regulated mainly by the stream energy available, the smoothness of the stream profile, and the resistance to erosion of the vegetation-soil-rock complex. As might be expected, the influence of these factors may range widely over short distances, e.g., from one drainage course to the next. The inherent strength of the rocks or soil, or the added strength imposed by the root mat of a heavy cover of trees or broad leafed chaparral, may offset the subtle effects of drainage development on the landslide process and slope erosion will proceed by other than those mechanisms described here.

LANDSLIDES RELATED TO DRAINAGE EVOLUTION

The model proposed here to explain landslide occurrence is based on a sequence of events that is common to the streams of Groups I and II and fits into the general framework of a shoreline of emergence as proposed by Putnam (1937). The streams of these two groups differ mainly in the time required for each to establish a connection with the sea and then to reach equilibrium between the capacity of the channel and the volume of stream flow. Once the connection is made this initiates a period of landslide activity which ends when equilibrium is established. The evolution of the drainage appears to occur in four stages:

Stage 1. A highland area adjacent to the shoreline is eroded by marine processes leading to the development of a sea cliff (figure 7). The highland area is drained by streams whose flow is derived from drainage basins far inland and by local streams that flow out of relatively small drainages nearby.

Stage 2. Sea level drops relative to the land, lowering base level and exposing the nearshore portion of the former sea floor. This platform becomes covered with a layer of beach or marine terrace deposits as the sea retreats. The terrace deposits are in turn covered by alluvial fans when the carrying capacities of the streams are diminished upon encountering the shallow gradient of the terrace surface. Stream flow is dissipated by numerous distributaries on the fan surface and by percolation into the poorly consolidated alluvial deposits. Early drainage of the terrace is on or through the surficial debris and out to the edge of the terrace generally above the bedrock platform. Later drainage forms from the development of gullies back from the modern sea cliffs (figures 8 and 9). The gullies subsequently enlarge and erode headward toward the main sources of flow at the edge of the alluvial fan or to incipient channels that may have developed on the terrace surface. One of these gullies eventually captures a distributary and establishes a direct conduit across the terrace from the inland segment of the stream course to the sea (figure 10).

Stage 3. With all the other distributaries bypassed, the full flow of the main stream is channeled into one narrow stream course. Erosive energy is concentrated in two directions: 1) downcutting of the stream bed, and 2) lateral cutting or undercutting of the slopes (figures 11 and 12A, B). The narrowness of the stream course, especially near the back of the terrace, promotes lateral erosion with an attendant increase in steepness of the slopes. Downcutting mainly increases the height of the slope. Landslide activity is most common during this stage, when lateral support is being removed and the slopes are rapidly becoming steeper and higher (figures 13 and 14).

Stage 4. After the stream channel on the terrace has been enlarged to accommodate the normal flow, and both segments of the stream course have developed a common, long profile, equilibrium is restored and landslide activity wanes (figures 15 and 16).

Discussion

Landsliding along stream courses in the terrace terrain can be explained by the concentration of both vertical and lateral erosive energy. Where stream flow rates are relatively low (Group II streams) the development of a long and reasonably regular profile is correspondingly slow, and the evolution of the drainage follows a somewhat different pattern than that of streams with relatively higher flow rates (Group I). Streams of high flow rate rapidly develop a continuous artery across the terrace terrain during a drop in sea level. They either race across the newly exposed, poorly consolidated marine deposits and cut a channel headward from the sea, or they flow over the edge of any newly formed sea cliff and rapidly develop a gully that deepens to accommodate the flow as it erodes headward. Landsliding and sloughing of the stream banks occur at this time and stream flow quickly carries the debris away. In this case, the erosive energy of the stream is fully augmented by the drop in base level. With extra energy and with the stream flowing in weakly

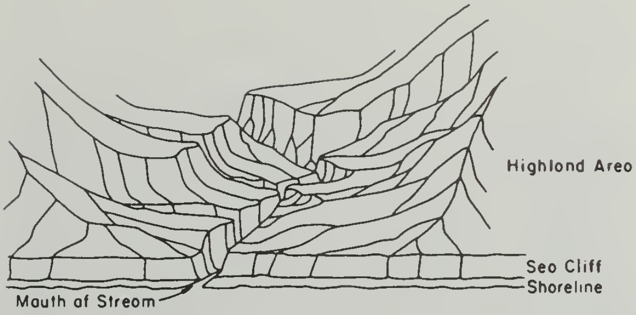


Figure 7. Stage 1 of drainage development on terrace terrain.

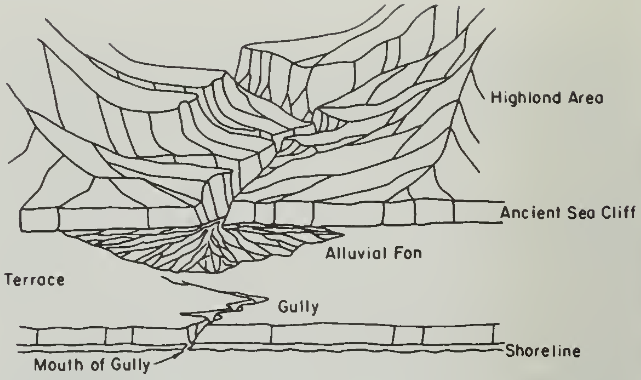


Figure 8. Stage 2 of drainage development on terrace terrain.

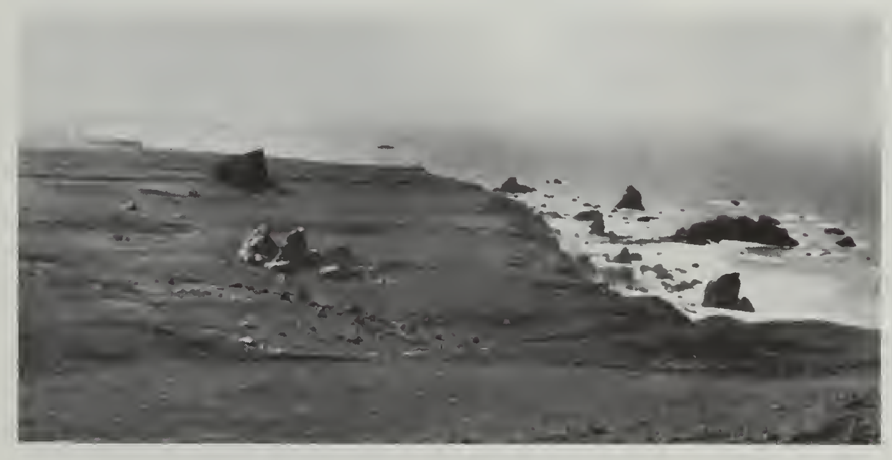


Figure 9. Development of gullies back from sea cliff on a terrace just south of the Russian River, Sonoma County.

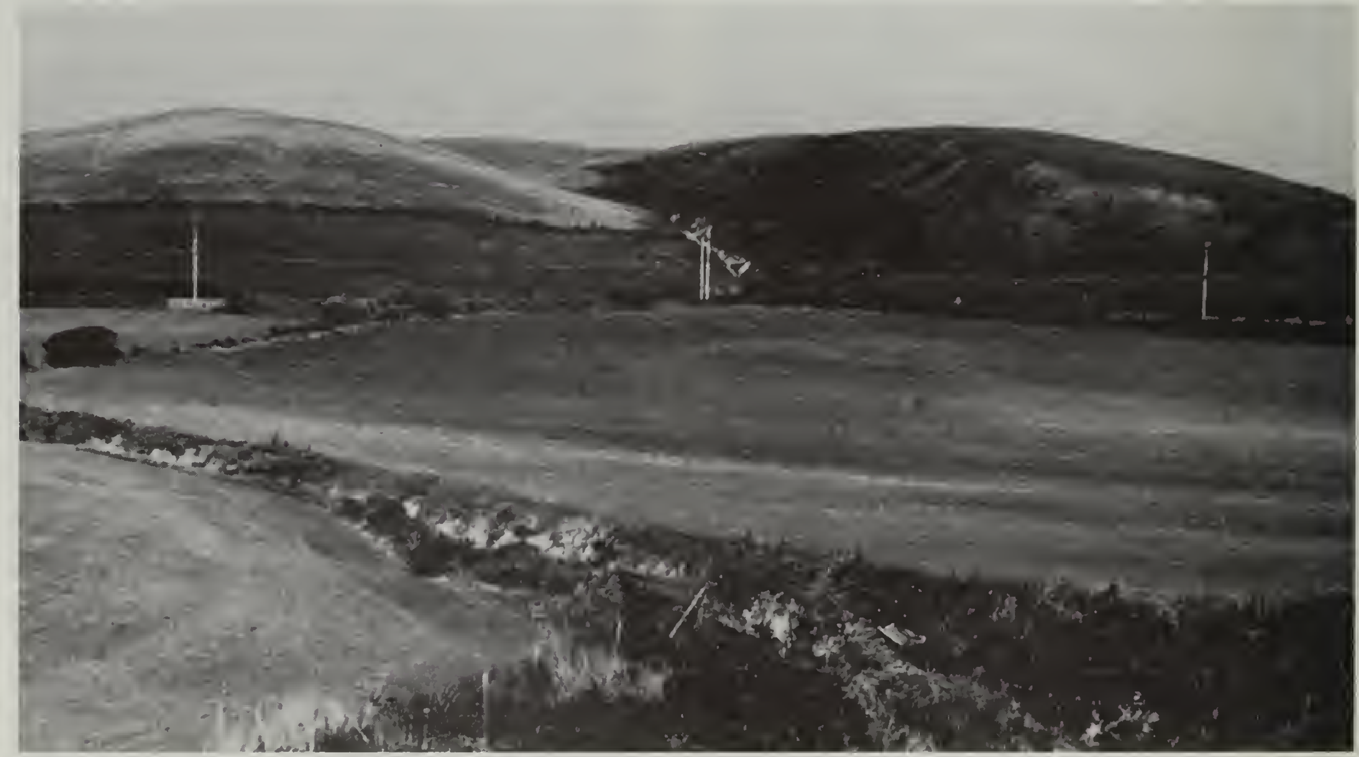


Figure 10. Recent capture of inland drainage by headward erosion of gully across terrace. The terrace surface is in the foreground with a broad alluvial fan at the base of the ancient sea cliff. The establishment of a lower base level has accelerated erosion on the stream segment above the terrace, leading to minor landsliding. Santa Cruz County coast.

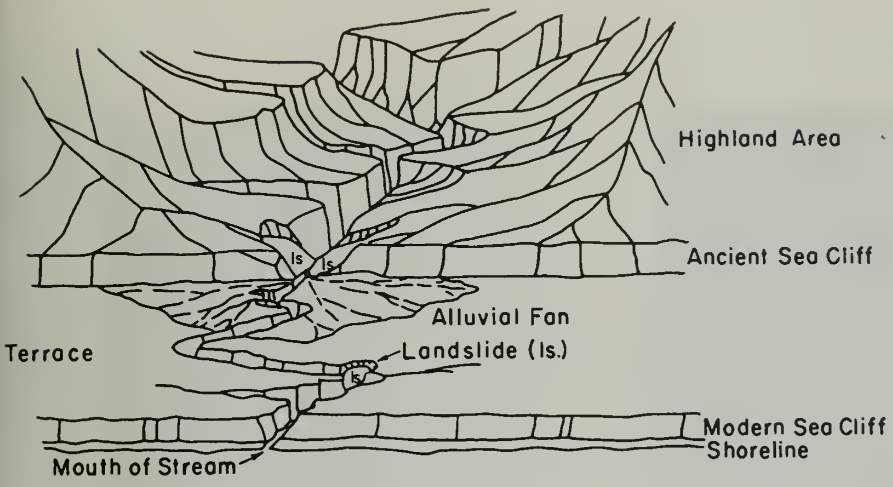


Figure 11. Stage 3 of drainage development on terrace terrain.

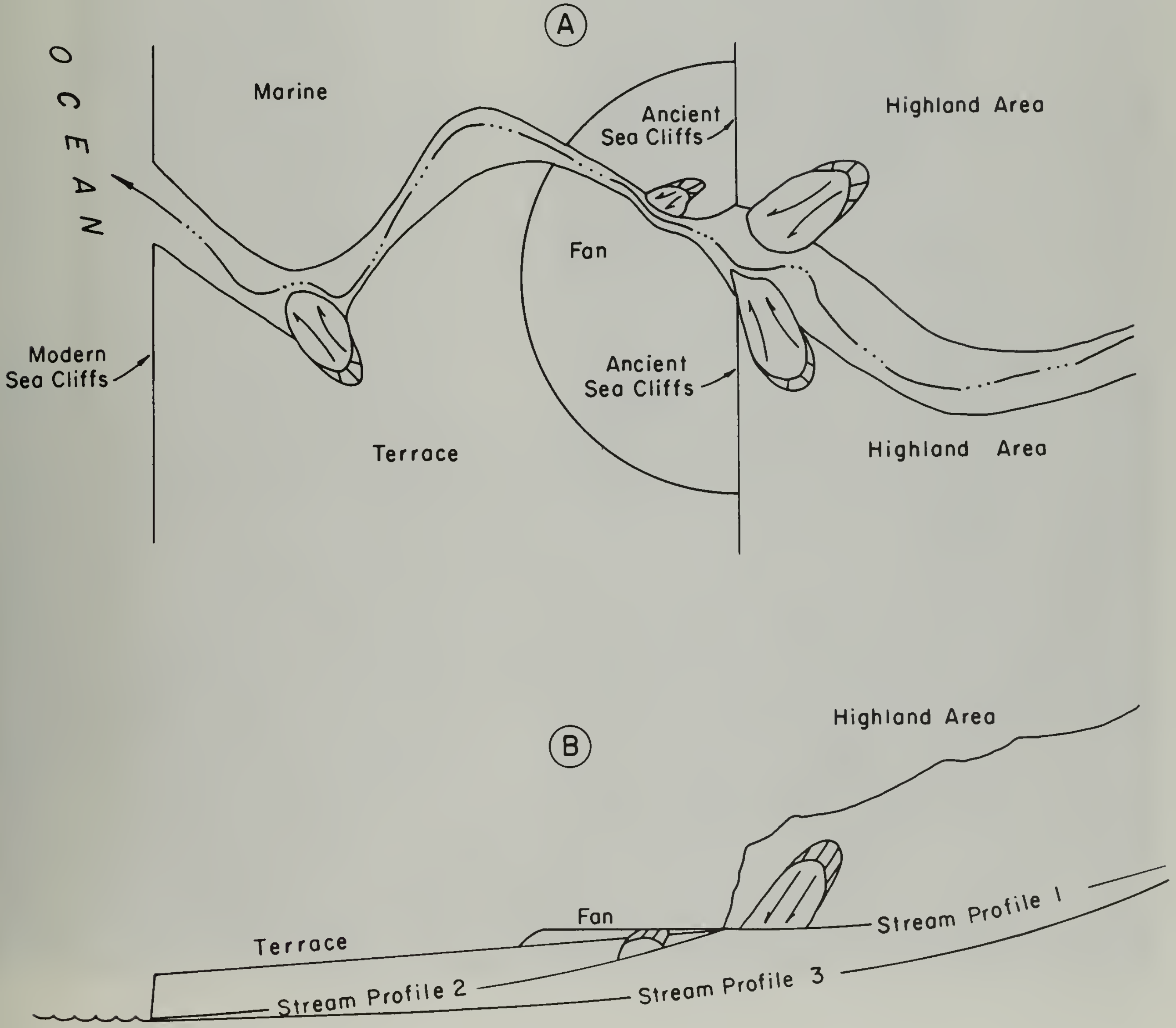


Figure 12. Diagram of stage 3 of drainage development.

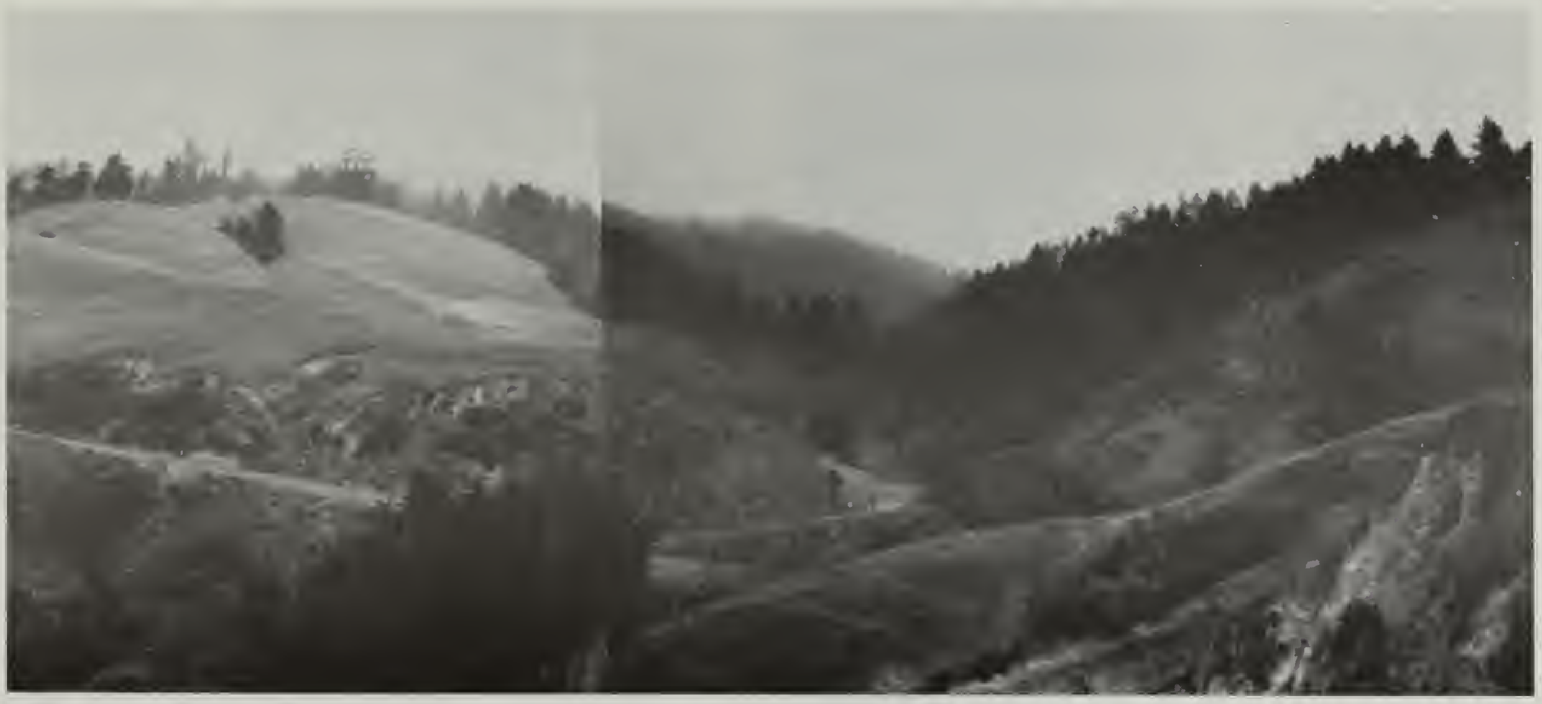


Figure 13. Highly disturbed terrace terrain along a stream in stage 3 of development, south of Fort Ross, Sonoma County.

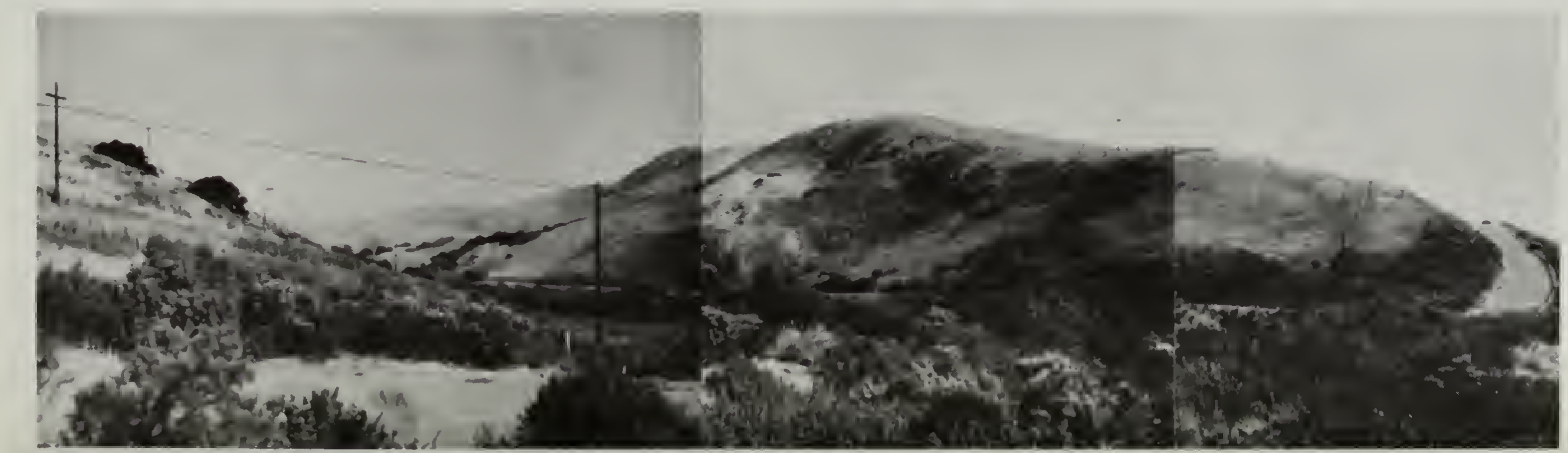


Figure 14. Landslide terrain upstream from terrace surface (foreground) during stage 3 of development. An ancient sea cliff is at the left and at right above the road; a cliff at a higher elevation is left of the double power pole. Santa Barbara County coast.

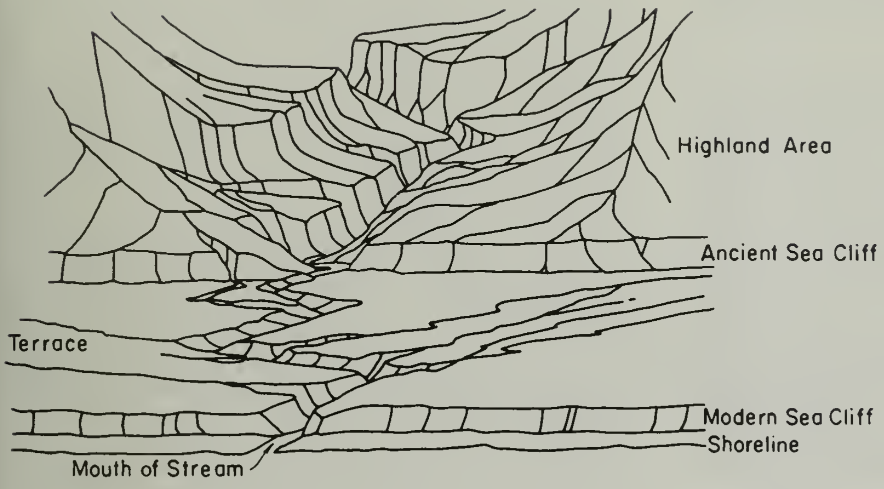


Figure 15. Stage 4 of drainage development on terrace terrain.

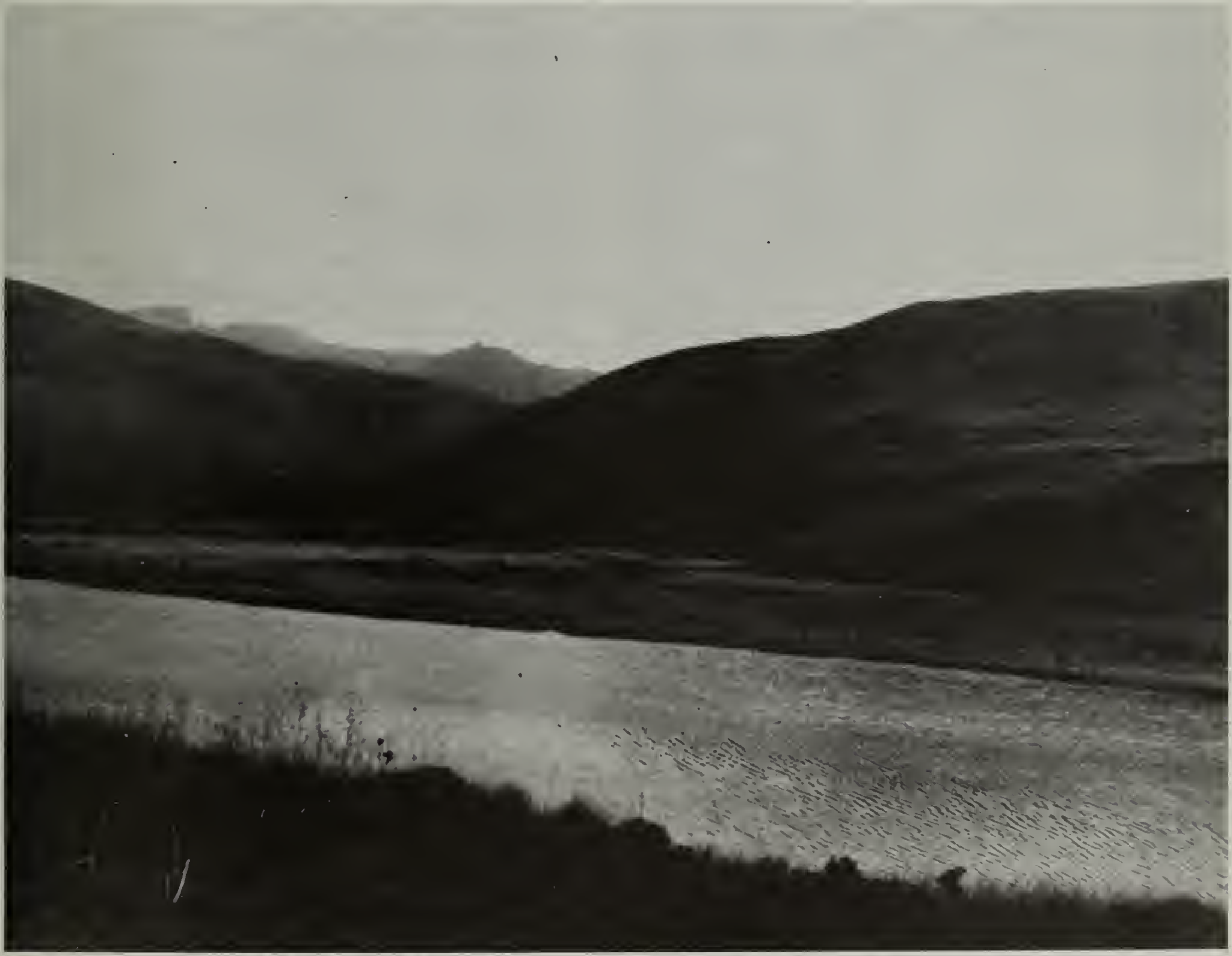


Figure 16. Stream approaching stage 4 of development where channel capacity can accommodate flow without extensive erosion. Salmon Creek, Sonoma County.

consolidated sediments, stream channel development is rapid. The base level of the stream is maintained with that of sea level all during drainage development.

Low flow streams (Group II) are not directly connected with the sea following a drop in sea level, and their regimen continues along a local base level, that of former sea level. With the drop in sea level the stream builds an alluvial fan at its "mouth" near the back of the terrace. As the fan grows, a larger spreading area becomes available for the dissipation of stream flow. The development of the terrace drainage proceeds headward from the modern sea cliffs toward the back of the terrace (figure 8). The base level of this segment is sea level. When it captures a distributary on the fan, the stream for the first time is integrated with sea level. It is then that the low flow stream (Group II) undergoes the geomorphic development that the high flow stream (Group I) underwent at the time of the original drop in sea level.

The difference between geomorphic development in low flow and high flow streams is the slower rate of change in the low flow stream. For example, the low flow stream must, after capture has occurred, cut through an added alluvial cover on the terrace. It is also likely that the marine terrace deposits have become better consolidated and, therefore, are more resistant to erosion than recently exhumed sea floor deposits. The most important difference between Group I and Group II streams, however, is that Group I streams maintain a continuous conduit with falling sea level, whereas Group II streams achieve a connection abruptly upon capture of the upper segment by a younger lower segment of what becomes a single drainage course. When capture takes place, the full flow of the inland stream segment is suddenly diverted into the recently established and inadequate terrace stream segment. The sudden release of stream energy following capture concentrates erosive energy all along the lower segment of the stream on the terrace surface, but especially near the back of the terrace where the capacity of the stream bed to accommodate the flow is most restricted (figure 12A). Until the stream bed capacity is in equilibrium with flow, downcutting, and especially lateral or under-cutting, will remove slope support and increase landslide propensity.

With any subsequent drop in sea level a resurgence of similar activity will begin to modify existing terraces, superimposing its effect on the combined effects of previous fluctuations in sea level.

The gradient of an established stream in the highland area and its relationship to the gradient of the segment which subsequently develops on the terrace terrain, following emergence, may determine if the stream aggrades or erodes its bed. Landsliding, of course, is associated with erosion. If the stream profile in the highland area is steeper than that of the profile in the terrace terrain the stream is likely to aggrade. The carrying capacity of the headward segment of the stream will decrease where it meets the gentler terrace segment and deposition will occur at this point. Conversely, if the highland segment is more gentle than the terrace segment of the stream, a knickpoint will then migrate headward as the lower segment of the stream excavates the rock that lies between the profiles of the two segments and that of a deeper, more mature long profile (figure 17). This relationship was suggested by M. J. Kirkby and Anne V. Kirkby (1969, H 39) based on their observations of stream development on raised beaches.

The part of the stream channel that crosses the terrace develops a short profile, the gradient of which is largely dependent upon the elevation at the head of the terrace and the distance to the sea. If the retreat of the sea cliffs by marine erosion exceeds that of the migration of the knickpoint, this segment of the stream will be shortened and the gradient steepened (figure 18). Erosive energy would then be accelerated and landslide activity increased. Therefore, landslides may be more common per unit area along rapidly eroded shorelines where the terraces are narrow and deeply eroded, and where the gradient of the terrace segment of the stream courses is relatively more steep (figure 6).

Experimental evidence suggests that downcutting of the stream bed occurs initially after a drop in base level and prior to any significant, lateral erosion (Yoxall, 1969, p. 1382). This leads to the migration of a knickpoint headward, increasing the height of the slopes and resulting in a maximum increase of slope height just upstream from the head of the terrace (figure 12B). Yoxall (1969, p. 1384) further demonstrated that the rate of lateral erosion in unconsolidated deposits is directly related to the rate of drop in base level. Therefore, along rapidly emerging coastlines, stream channels would be subjected to accelerated lateral erosion with attendent development of landslides.

Landslide propensity can be estimated by determining to which group a stream belongs. Slopes of Group II streams are, at the present time, most prone to landslides. However, many ancient landslides are preserved along the stream courses of Group I because of the reduced erosive energy subsequently available to excavate and destroy them and by their being buttressed against channel deposits. Streams of Group II can be further evaluated by noting just how much out of equilibrium they are in terms of the capacity of the channel to accommodate the stream flow. This can be established by observing the relative preservation of channel features characteristic of Group II streams, compared with those of Group I streams (table 2). The relative preservation of the marine and nonmarine terrace cover will indicate the degree to which any weak bedrock formation may be protected from erosion. Landsliding appears to be more common in the terrace terrain where part or all of the cover has been eroded away.

Evidence of Drainage Development After the Alaska Earthquake

The development of new drainage on an emerged segment of coast following the Alaska

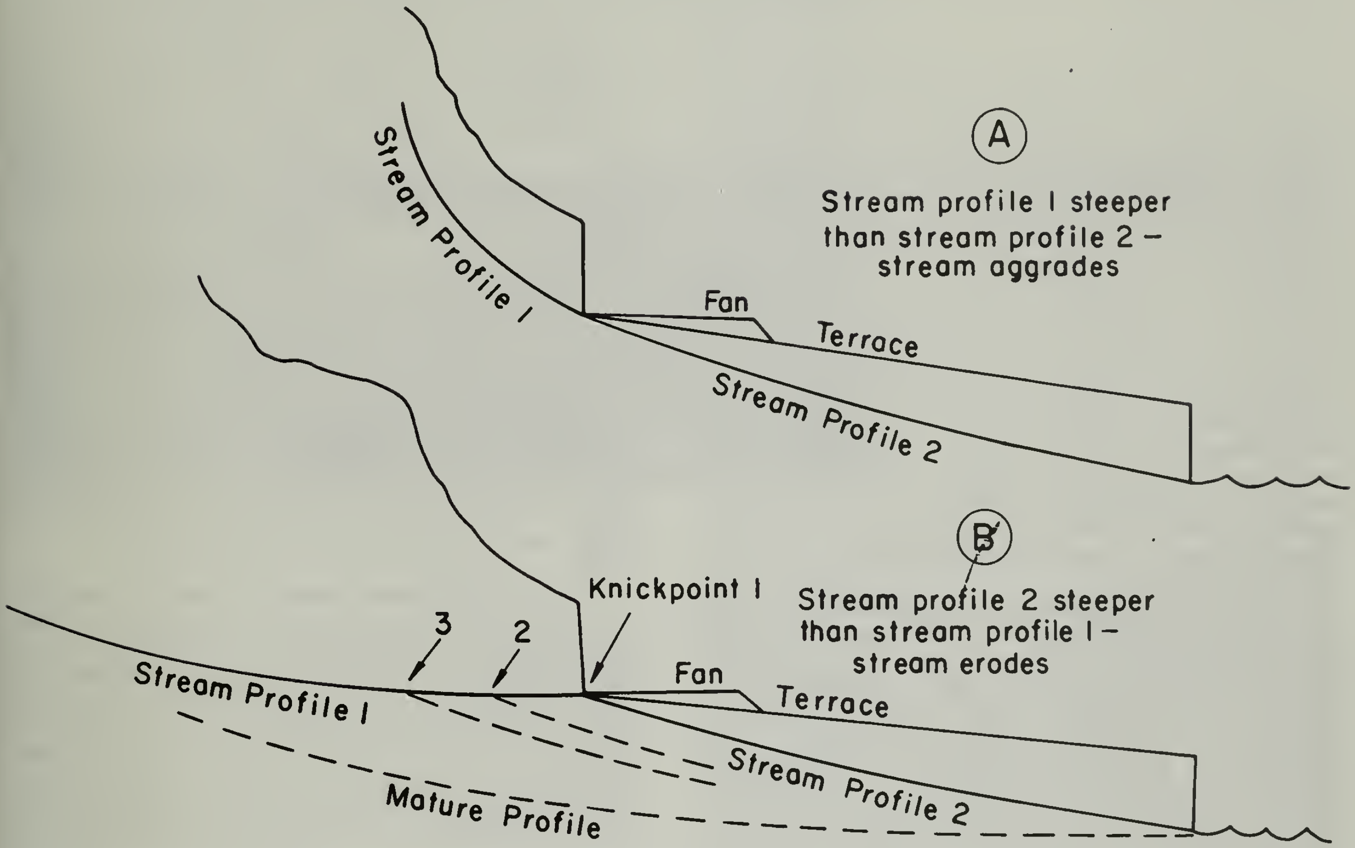

A
Stream profile I steeper than stream profile 2 – stream aggrades
Stream Profile I
Fan
Terrace
Stream Profile 2
B
Stream profile 2 steeper than stream profile I – stream erodes
Knickpoint I
3
2
Stream Profile I
Fan
Terrace
Stream Profile 2
Mature Profile

Figure 17. Relationship between stream gradients and aggradation or erosion.

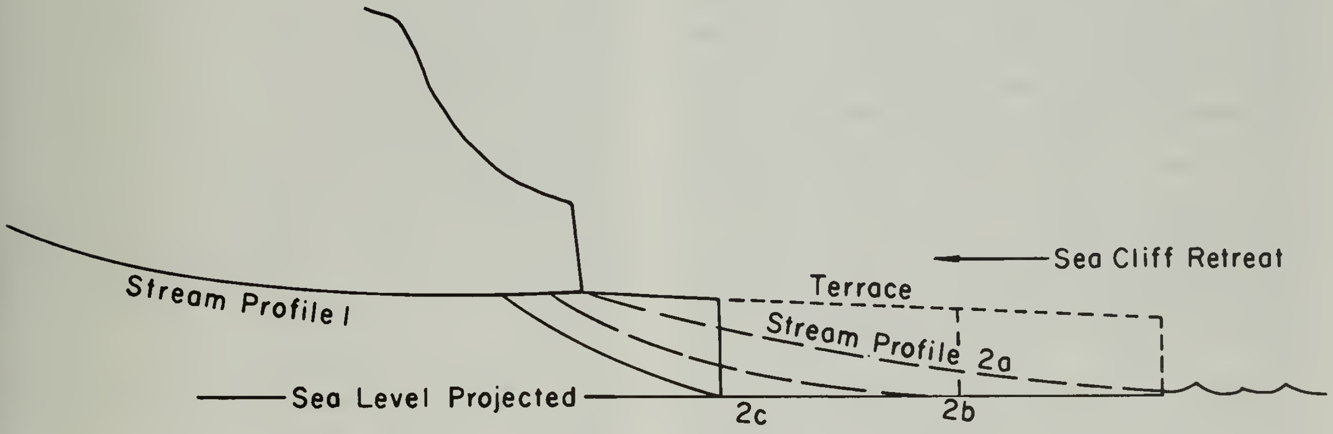


Figure 18. Stream gradient and sea cliff retreat.

earthquake in 1964 provides a modern analog to some of the geologic events that are taking place or have been recorded in the terrace terrain of the California coast.

Uplift during the Alaska earthquake elevated the shore line of Montague Island, off the south coast of Alaska, as much as 33 feet and exposed unconsolidated sand, gravel, and deltaic bay-head deposits to subareal erosion. Subsequent changes in the geomorphology during the months following the earthquake were recorded by Kirkby and Kirkby (1969) who showed that consequent streams rapidly developed on the newly emerged sea floor. Streams with flow rates greater than 10 cubic feet per second cut down through the unconsolidated sand and silt deposits on the emerged sea floor and established uniform gradients between the old and the new sea levels within days; those with lower flow rates still had knickpoints after 15 months. The former sea cliffs above the raised platform eroded back and the base of the cliffs became mantled with talus and landslide debris. Where streams cut through the cliffs, alluvial fans developed locally at the back of the raised platform.

The rapid development of stream courses in the unconsolidated deposits led to high rates of erosion including landsliding. During the first 2 months following the earthquake, erosion amounted to a total of 12 million cubic feet for all streams studied. However, erosion was much more rapid in the following 13 weeks when 38 million cubic feet of debris was excavated. After this period the rate of erosion dropped, but observations continued up to 15 months after the earthquake, when total erosion had reached about 88 million cubic feet (Kirkby and Kirkby, 1969, H 9).

From the analysis of vertical and lateral erosion on two streams, it was inferred that lateral erosion took place largely after most vertical erosion was complete (Kirkby and Kirkby, 1969, H 9). This corresponds with Yoxall's (1969) experimental results. By comparing the total volumes of debris yielded by all the streams described above during the inferred time periods of mainly vertical and then mainly lateral erosion, the relative volumes of debris yielded by each mechanism can be roughly estimated. It would appear that during the 15 month period of observation, mostly vertical and some lateral erosion yielded 12 million cubic feet of debris in the first 2 months. In the remaining 13 months, 76 million cubic feet of debris was derived largely by lateral erosion. Without knowing the relative amounts of debris yielded by each mechanism during the initial 2-month period, the relationship still suggests that lateral erosion is several times more effective than vertical erosion in enlarging the capacity of the stream courses immediately following a sudden drop in sea level.

The events in Alaska represent only the early part of the evolution of a terrace and, therefore, are not entirely comparable to the longer history recorded for terraces in California. In Alaska, stream activity was measured in unconsolidated sediments on a raised beach and during the period of observation none of the streams cut down any significant degree into the bedrock platform below. Therefore, the analogy is reduced largely to a comparison of stream development on raised beaches with similar developments on the marine terrace deposits (ancient beaches) of California.

LANDSLIDES RELATED TO ANCIENT SEA CLIFFS

The headlands and embayments of the modern coastline define zones of strength and weakness which are governed by a variety of factors (figure 19). While stability analysis of the modern coastline is beyond the scope of this presentation, some of these same factors apply to the ancient sea cliffs as well (figure 20). Embayments in these old cliffs, which were not formed by stream erosion, like their modern counterparts mark inherently weak slopes which may be the sites of ancient and modern landslides.

The intersections of stream channels with the modern and ancient sea cliffs are common localities for landslides. The landslides develop on the facet that marks the junction between the cliff face and either slope of the stream course. The development of this point of land by both modern stream and, in the past, by ancient marine erosion weakens the rocks by removing support on two adjacent slopes. Thus, potential slide planes are established across the point along which a landslide can occur (figure 21).

The steepness of the lower part of the ancient sea cliff is commonly preserved by a wedge of ancient or modern talus banked against the base of the cliff. The exposed steep upper part of the slope promotes rapid runoff subjecting the talus to gullying. The gullies commonly originate at the lower edge of the talus deposits and generally terminate up on the cliff where the deposits are relatively thin. The thick accumulations of talus at the base of the slope are generally poorly consolidated and, if coarse grained, they may erode to badland type morphology, especially in dry climates. Finer grained deposits and more humid conditions lead to mass failures. Landslides along the gullies are relatively minor features but, under suitable conditions, they may take the form of mudflows and become significant in terms of their destructive capability and potential threat to life.

Ground water accumulation at the contact between the bedrock and the overlying surficial deposits commonly migrates seaward. When it emerges on the face of the modern or ancient sea cliff and runs down over the surface, a thin column of rock may become saturated and slough off. Such incipient erosion of the cliff face can eventually lead to an oversteepened slope or to an overhang and subsequently to a major landslide in the form of a slump or rockfall.

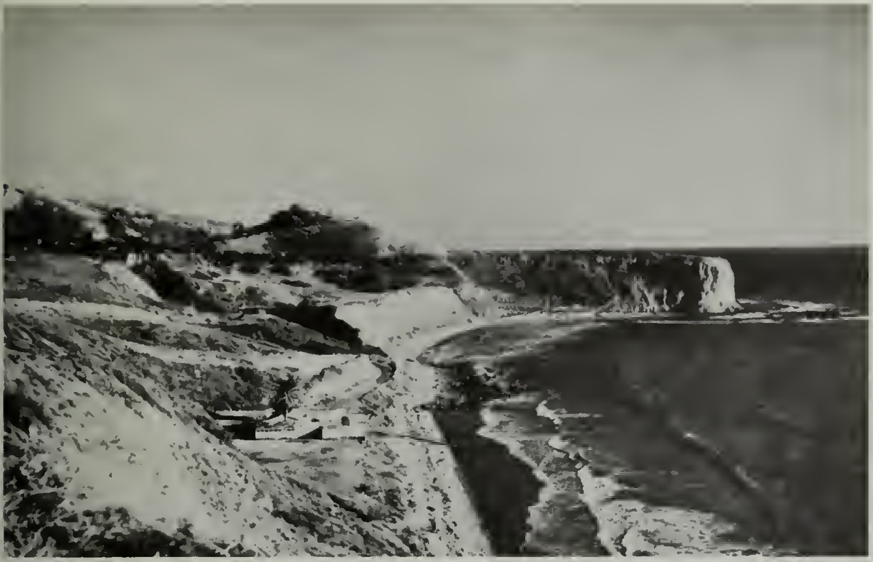


Figure 19. Coastal embayment eroded into landslide debris contrasts with undisturbed rocks forming point at right. Palos Verdes Hills, Los Angeles County coast.

Relatively Stable Zones in Terrace Terrain

Terrace deposits over broad areas are strongly cemented and highly resistant. Bedrock units below the terrace deposits also may be inherently strong so that they are not subject to massive failure. The slopes along some major drainages have been naturally buttressed by stream deposits. Elsewhere, both ancient and modern talus deposits and fanglomerates buttress slopes and reduce the likelihood of landsliding.

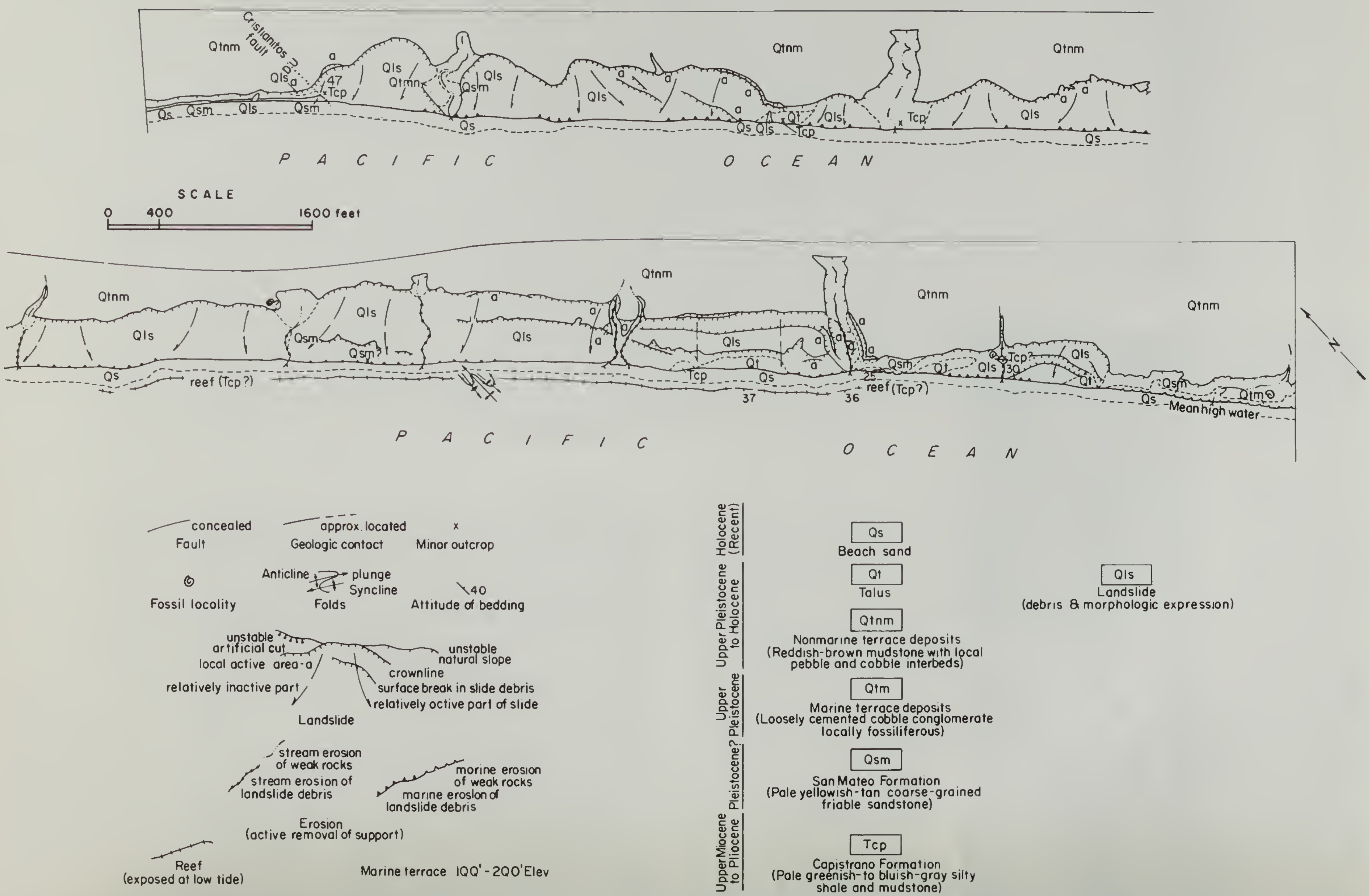
Terraces generally have had their greatest development where the bedrock was inherently weak. Therefore, the terraces commonly are mantled with weak deposits. In some areas the terrace cover has been cemented subsequently, yielding a thick crust which armors the surface and inhibits landsliding. This has occurred in the San Diego coastal area where locally ferruginous deposits have cemented the terrace materials. Cementation has also occurred along the north coast, in Mendocino County, near Fort Bragg, where hardpan deposits form resistant layers a few inches to a few feet below the surface of the terraces overlying highly resistant bedrock. Resistant bedrock underlies the terraces locally just west of the city of Santa Cruz and landslides are scarce in these rocks. Those landslides that do form are generally the product of stream undercutting of the resistant layers.

Streams graded to lower base level (Group I), probably during Wisconsin time, are now flooded near their mouths. With the subsequent rise in base level, these streams have been aggrading their lower reaches. Numerous examples of these drowned stream mouths occur along the coast. Upson (1949; 1951) made detailed studies of some of their occurrences along the California coast. It was Stout (1969, p. 178), however, who pointed out the slope stability implications of sediment deposition. He suggested that a previously formed landslide could be substantially buttressed by the deposition of fluviatile or marine deposits against the toe of the slide. Although this is effective in blocking movement on the original slide plane, slip planes can develop in the debris mass above the buttress, leading to renewed landsliding at a higher elevation.

Talus deposits preserved locally along the modern sea cliffs form an ephemeral buttress that somewhat increases stability (figure 22). More important in terms of stability inland are similar but older talus deposits banked against the ancient sea cliffs (figure 23). These deposits are relatively thicker because they have had a longer time to accumulate and have not been subjected to removal by marine erosion. Moreover, the talus debris may be cemented and, therefore, forms a stronger buttress. Being older, the upper part of the ancient cliffs are more highly eroded; therefore, the talus buttresses slopes are relatively less steep than those of their modern counterparts.

The occurrence of talus may be an indication that it was derived from a relatively stable slope. The accumulation and preservation of talus depends on the parent rocks being composed of inherently strong material and thus the sea cliff relatively steep and stable.

The ancient fanglomerate at the head of the terraces can form a secondary buttress. These deposits may lie against the cliffs or against any previously deposited ancient talus, reinforcing the old sea cliffs at their base.


Qtnm
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37
36
30
Tcp?
Qtm
Mean high water
N
concealed
Fault
approx. located
Geologic contact
x
Minor outcrop
Fossil locality
Anticline
plunge
Syncline
Folds
40
Attitude of bedding
unstable artificial cut
local active area-a
relatively inactive part
unstable natural slope
crownline
surface break in slide debris
relatively active part of slide
Landslide
stream erosion of weak rocks
stream erosion of landslide debris
marine erosion of weak rocks
marine erosion of landslide debris
Erosion (active removal of support)
Reef (exposed at low tide)
Marine terrace 100'-200' Elev
Holocene (Recent)
Upper Pleistocene to Holocene
Upper Pleistocene
Pleistocene?
Upper Miocene to Pliocene
Qs Beach sand
Qt Talus
Qtnm Nonmarine terrace deposits (Reddish-brown mudstone with local pebble and cobble interbeds)
Qtm Marine terrace deposits (Loosely cemented cobble conglomerate locally fossiliferous)
Qsm San Mateo Formation (Pale yellowish-tan coarse-grained friable sandstone)
Tcp Capistrano Formation (Pale greenish-to bluish-gray silty shale and mudstone)
Qls Landslide (debris & morphologic expression)

Figure 20. Geology of the San Onofre Bluff area, San Diego County, California. *From Cleveland, 1971.*

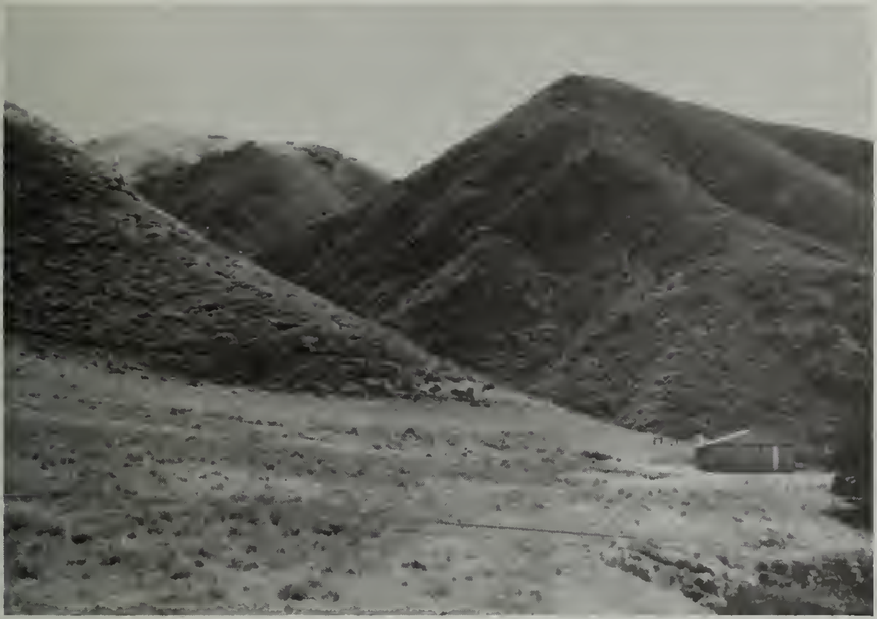

Figure 21. Landslide at junction of stream slope with ancient cliff face. A terrace can be seen in the foreground. An ancient sea cliff is at the back edge and a higher, poorly preserved terrace bench with eroded cliff face above is visible on the far slope. Mendocino County coast.

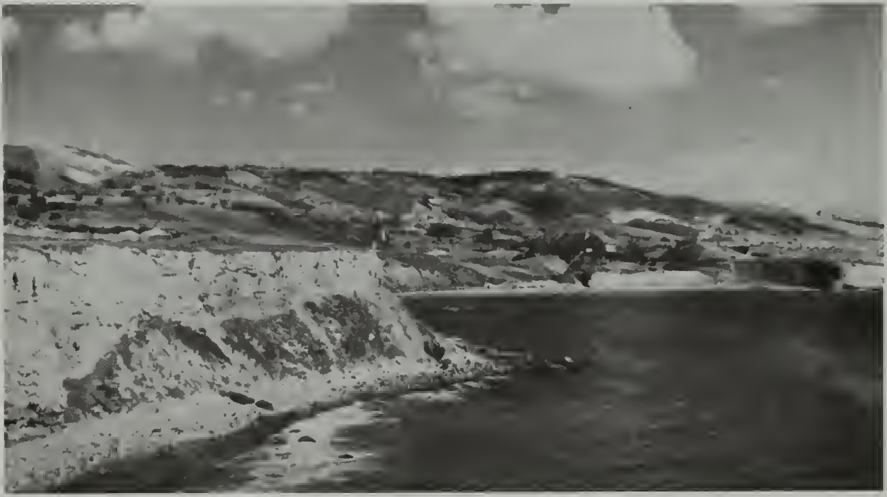

Figure 22. Talus banked against modern sea cliff. Similar deposits exist locally along ancient sea cliffs at higher elevations in the background. Palos Verdes Hills, Los Angeles County coast.

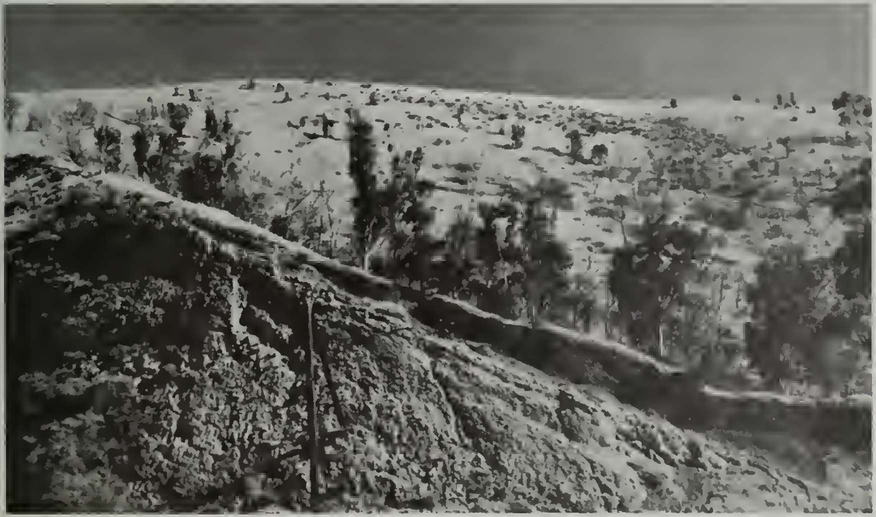

Figure 23. Cross section of ancient sea cliff, Palos Verdes Hills, Los Angeles County coast. Wedge of light colored talus, right, lies on beveled off bedrock, left, along diagonal contact that marks the ancient sea cliff. Dark colored deposit lying on talus is modern slope wash deposit. Elevation 300 feet above sea level.

CONCLUSION

Regional landslide propensity in marine terrace terrain can be estimated in part by evaluating the stage of drainage development and by determining the distribution and nature of surficial materials deposited during terrace evolution. When applied to similar geologic terrains, the results of this study suggest the following relationships:

1. Present landslide activity is more common along streams of relatively low flow rate (Group II) that were late in establishing a channel to the sea after low sea stands, and which have not yet reached equilibrium between the capacity of the channel and its ability to accommodate the stream flow.
2. Ancient landslides may be preserved locally along streams with relatively high flow rates (Group I) which have maintained a nearly continuous channel to the sea during periods of sea level fluctuation.
3. Landslides are most common along stream courses near the backs of terraces and directly upstream where vertical and lateral erosive energy is concentrated.
4. Landslides may be more common along rapidly eroding shorelines where present terraces, or the terrace belt generally, are narrow and the gradient of the stream course is relatively steep.
5. During terrace development, local deposition of various types of surficial deposits by marine or fluviatile processes may increase stability of adjacent slopes.

REFERENCES

Birkeland, P.W., 1972, Late Quaternary eustatic sea-level changes along the Malibu coast, Los Angeles County, California: Journal of Geology, v. 80, no. 4, p. 432-448.

Blanc, R.P., and Cleveland, G.B., 1968, Natural slope stability as related to geology, San Clemente area, Orange and San Diego Counties, California: California Division of Mines and Geology Special Report 98, 19 p.

Bloom, A.L., 1972, Glacial-eustatic and isostatic controls of sea level since last glaciation *in* Karl K. Turekian, editor, The Late Cenozoic glacial ages: Yale University Press, New Haven, p. 355-379.

Bradley, W.C., 1957, Origin of marine-terrace deposits in the Santa Cruz area, California: Geological Society of America Bulletin, v. 68, no. 4, p. 421-444.

Bradley, W.C., and Addicott, W.O., 1968, Age of first marine terrace near Santa Cruz, California: Geological Society of America Bulletin, v. 79, no. 9, p. 1203-1210.

Cleveland, G.B., 1967, Preliminary geologic map of the Palos Verdes Hills, Los Angeles County, California: California Division of Mines and Geology, open file release.

Cleveland, G.B., 1971, Geology of proposed state park at San Onofre Bluff, San Diego County, California: California Division of Mines and Geology, unpublished report, 11 p.

Gary, Margaret, McAfee, Robert Jr., and Wolf, C. L., editors, 1972, Glossary of geology: American Geological Institute, Washington D.C., 857 p.

Jahns, R.H., and Cleveland, G.B., 1962, Geology related to engineering, Palos Verdes Peninsula, Los Angeles County, California: California Division of Mines and Geology, unpublished report.

Kirkby, M.J., and Kirkby, A.V., 1969, Erosion and deposition on a beach raised by the 1964 earthquake, Montague Island, Alaska: U.S. Geological Survey Professional Paper 543-H.

Palmer, L.A., 1964, Marine terraces of California, Oregon and Washington: unpublished Ph.D. dissertation, University of California, Los Angeles, 379 p.

Putnam, W.C., 1937, The marine cycle of erosion for a steeply sloping shoreline of emergence: Journal of Geology, v. 45, no. 8, p. 844-850.

Slosson, J.E., and Cilweck, B.A., 1966, Parson's Landing landslide, a case history including the effects of eustatic sea level changes on stability: Engineering Geology, v. 3, nos. 1 and 2, p. 1-9.

Stout, M.L., 1969, Radiocarbon dating of landslides in southern California and engineering geology implications *in* S. A. Schumm and W.C. Bradley, editors, United States contributions to Quaternary research: Geological Society of America Special Paper 123, p. 167-169.

Upson, J.E., 1949, Late Pleistocene and Recent changes of sea level along the coast of Santa Barbara County, California: American Journal of Science, v. 247, p. 94-115.

Upson, J.E., 1951, Former marine shore lines of the Gaviota quadrangle Santa Barbara County, California: Journal of Geology, v. 59, p. 415-446.

Valentine, J.W., and Veeh, H.H., 1969, Radiometric ages of Pleistocene terraces from San Nicolas Island, California: Geological Society of America Bulletin, v. 80, no. 7, p. 1415-1418.

Veeh, H.H., and Valentine, J.W., 1967, Radiometric ages of Pleistocene fossils from Cayucos, California: Geological Society of America Bulletin, v. 78, no. 4, p. 547-550.

Wahrhaftig, Clyde, and Birman, J.H., 1965, Quaternary of the Pacific Mountain System in California *in* The Quaternary of the United States: Princeton University Press, p. 299-340.

Yoxall, W.H., 1969, The relationship between falling base level and lateral erosion in experimental streams: Geological Society of America Bulletin, v. 80, no. 7, p. 1379-1384.